IMPROVED BLIND POINTING OF NASA'S BEAM-WAVEGUIDE ANTENNAS FOR MILLIMETER WAVE OPERATION

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I. INTRODUCTION

NASA's Deep Space Communications Network (DSN) consists of three complexes of large antennas located at Goldstone, California, Madrid, Spain, and Canberra, Australia. Each of these contains a number of 34-meter aperture plus a single 70-meter aperture, shaped dual reflector antennas, all of which were originally designed as low noise, high gain systems for operation at S- and X-band (2295 MHz and 8400 MHz).

The demands of future space missions for the scientific exploration of the solar system and beyond, extending well into the new millennium, have resulted in the need for considerably improved system capability with respect to data rates and total data handling capacity, and a key element in achieving these is a system wide upgrade to Ka-band operating frequencies (32 GHz). The requirements of telemetry, as well as radio science, which utilizes the unmodulated carrier for a variety of experiments such as profiling planetary and satellite atmospheres and gravity wave searches, demand highly accurate, all-sky antenna pointing in order to minimize signal variation and phase distortion, and the pointing requirements at Ka-band present serious challenges for the 34-meter and 70-meter antennas.

In order to meet these challenges it will be necessary to significantly improve both the blind pointing and closed loop pointing capabilities of these antenna systems. This paper describes work undertaken to improve the *blind pointing* accuracy of NASA's 34-meter Beam Waveguide (BWG) antennas, which form the core of the entire network. The Blind Pointing Task has isolated the following major contributors to the residual pointing errors of these antennas:

1) Inaccuracy of pointing measurements, 2) Azimuth track level errors, 3) Thermal distortions of the antenna structure, 4) Mechanical hysteresis, and 5) Azimuth encoder gear errors,

and these are discussed below.

II. MEASUREMENT OF POINTING ERRORS

The conventional approach to determining the pointing errors of DSN antennas has used boresight measurements on natural point radio sources of well known astrometric position. The boresight algorithm steps the antenna sequentially through a series of offsets located at - 5, - 1, 0, 1, and 5 half-power beamwidths (HPBWs) from the command position, first in cross elevation (XEL), then in elevation (EL). After subtraction of a linear baseline determined from the outer two measurements, the remaining three are used to determine the three coefficients of a Gaussian main beam power pattern of the form

$$T(\theta) = a_0 \exp\left[-(\theta - a_1)^2 / a_2^2\right] \tag{1}$$

by means of a logarithmic linearization, where $T(\theta)$ is the antenna temperature due to the source at offset position θ, and a_1 is the desired pointing correction which is used to correct the subsequent boresight in the orthogonal, ϕ direction, etc.

While this method has the merit of simplicity, and has been successfully used at S- and X-bands, it lacks the precision required for use at Ka-band, and consequently a different approach to these measurements based on the use of conical scanning of the antenna beam about the source (CONSCAN) has been developed. In the open-loop implementation used for pointing measurements, the CONSCAN radius is set close to the -3dB level to maximize the pointing error signal, and the data are reduced at the conclusion of ten or twelve 30 second scans. In addition, data rates of up to 4 per second are used, providing 120 points per scan, and permitting a corresponding increase in measurement signal-to-noise ratio (SNR).

The model used for the normalized antenna power pattern is the Airy pattern of classical diffraction theory, as this is a more realistic approximation to the actual beam pattern than the Gaussian function. Thus, the antenna temperature during the CONSCAN motion is assumed to be of the form

$$T(t) = a_0 + a_1 t + a_2 t^2 + a_3 P_n\left[\frac{2b}{a_4}\sqrt{\left[a_5 + a_6\theta(t)\right]^2 + \left[a_7 + \mathrm{v}(t-t_0) + \phi(t)^2\right]}\right], \tag{2}$$

where the quadratic polynomial accounts for changes in system operating temperature due to elevation changes during the scan, $P_n(x) = \left[2\frac{J_1(x)}{x}\right]^2$ is the Airy pattern, $b = 1.616$ is the value of x for which the slope of $P_n(x)$ is maximum, $\theta(t)$ and $\phi(t)$ are the XEL and EL quadrature sinusoids producing the circular scan motion, and $\mathrm{v}(t-t_0)$ is an EL ramp of angular velocity v started at $t = t_0$, about midway through the sequence, to move the beam through the source.

The XEL and EL components of the CONSCAN motion, $\theta(t)$ and $\phi(t)$, are determined from least-squares fits to the azimuth and elevation encoder data, and the parameter a_6 is included to allow for small departures of the beam motion from a pure circle due to the high acceleration of the antenna structure at high elevations. The remaining parameters have the following meanings: a_3 =source antenna temperature, T_{pk}, a_4 =HPBW, a_5 =XEL pointing error, and a_7 =EL pointing error. The seven parameters in (2) are determined from a nonlinear least-squares fit to the antenna temperature data, where the original estimates of these parameters are obtained from a linearized approximation to this equation corresponding to the first two terms in a Taylor expansion of $P_n(t)$.

This method of determining pointing errors, source antenna temperatures, and beamwidths, yields about an order of magnitude improvement in accuracy over the conventional boresight method when applied at X-band, with pointing errors determined to within 0.1 mdeg (0.36 arc sec), source temperatures to 1%, and HPBWs to within 1 mdeg (3.6 arc sec). While the method is applicable at Ka-band, the lack of radio sources of adequate brightness at these frequencies dictates a pointing measurement program at X-band, and fortunately it is a relatively straightforward matter to account for the differences in BWG antenna pointing at these two frequency bands.

III. AZIMUTH TRACK LEVEL COMPENSATION (TLC) SYSTEM

The pointing errors introduced by irregularities in the azimuth track have been measured by means of four precision tiltmeters mounted to the alidade structure of the antenna, numbers 1 and 2 directly under the elevation bearings, and 3 and 4 on the uppermost horizontal beams at the sides of the alidade. The measurements were conducted at a fixed elevation by scanning in azimuth over 360 degrees during a period of two hours centered at 2:00 AM local time, when the structure is observed to be near thermal equilibrium, and show very good repeatability from night to night.

The XEL and EL pointing errors due to rotations $\delta\Omega_x$, $\delta\Omega_y$, $\delta\Omega_z$, of the elevation axis about the x, y, and z alidade axes are given by

$$\delta\mathrm{xel} = -\delta\Omega_y \sin(\mathrm{el}) + \delta\Omega_z \cos(\mathrm{el}),\ \delta\mathrm{el} = -\delta\Omega_x, \tag{3}$$

where x, y, and z form a right handed coordinate system with x along the elevation axis, y horizontal and facing away from the antenna beam, and z vertical. The three rotation angles $\delta\Omega_x$, $\delta\Omega_y$, $\delta\Omega_z$, are determined from the tilts α and β of the x and y axes of the four tiltmeters, which are aligned parallel with the alidade x and y axes. Thus,

$$\delta\Omega_x = -\beta_2,\ \delta\Omega_y = -(1/2)(\alpha_1 + \alpha_2),\ \delta\Omega_z = (h/l)(-\alpha_3 + \alpha_4), \tag{4}$$

where h is the height of the elevation axis above the azimuth track, and l is the separation of the elevation bearings.

Comparisons of the EL errors predicted by the TLC model with those determined from CONSCAN pointing measurements were made over an azimuth track of about 120 degrees at a nearly constant elevation of 80 degrees, and show agreement within 0.2 mdeg (0.72 arc sec). Similarly, XEL comparisons agree within 0.3 mdeg. (1.08 arc sec) over the same track. The latter confirms the correctness of the equation for δxel at high elevations where the first term involving $\delta\Omega_y$ dominates. The predicted rotations $\delta\Omega_x$, $\delta\Omega_y$, $\delta\Omega_z$, due to azimuth track irregularities have a broad frequency spectrum and a maximum peak-to-peak amplitude of about 8 mdeg. They are stored in a look-up table and fed to the Antenna Pointing Control (APC) computer to provide corrections during normal spacecraft tracking.

IV. HYSTERESIS EFFECTS AND AZIMUTH ENCODER GEAR ERRORS

The coupling arrangement between the elevation axle and the elevation encoder was originally suspected of being responsible for an irregular hysteresis effect. The existence of this hysteresis was subsequently confirmed through a series of precision CONSCAN pointing measurements during which the antenna was slewed up and down in elevation in such a manner as to induce the effect.

The measurements showed a hysteresis amplitude roughly proportional to the amplitude of the elevation excursions during slew, with a maximum amplitude of about 4 mdeg. A more robust coupling shaft design employing two alignment bellows and using welded construction throughout was subsequently installed and the hysteresis measurements repeated with negative results, i.e., no hysteresis was observed with the new coupling arrangement.

In the original BWG antenna design, the azimuth encoder was driven by a segmented ring gear, and in spite of careful alignment of the individual gear segments, it was not possible to eliminate discontinuities in the encoder rotation due to the gaps between segments. The rms error in azimuth due to this gear was measured and found to be 5.2 mdeg (18.7 arc sec). In order to reduce this error a new, continuous ring gear design was implemented, and testing of this showed a total rms azimuth error of only 0.44 mdeg (1.58 arc sec), greatly reducing this source of pointing error. Additionally, indications are that, as in the case of the track level irregularities, the residual gear errors are repeatable so that even this small error can be reduced if desired.

V. THERMAL DISTORTIONS OF THE ANTENNA MECHANICAL STRUCTURE

An early thermal analysis of the alidade showed that insulating those members (bars) of the structure with the greatest sensitivity (mdeg/K) could reduce their expected diurnal temperature excursions from 26 K to 4 K, and the expected temperature differences between exposed and shaded bars from peak-to-peak diurnal values of 8 K to 2 K. Even at the lower figures, however, predictions based on the alidade FEM indicated residual pointing errors after insulating that exceeded the task goal of 2 mdeg mean radial error. Thus, it was decided to augment the thermal insulation of the sensitive alidade members with an Alidade Temperature Monitor (ATM) system, using temperatures from sensors mounted to the structure as input to a predictive model derived from the alidade FEM.

The ATM model, like the TLC model, is based on (3), where the thermally induced alidade rotations $\delta\Omega_x$, $\delta\Omega_y$, $\delta\Omega_z$, at time t_i are given by

$$\delta\Omega_x(t_i) = \sum_{j=1}^{M_A} \delta L_j(t_i) C_{xj},\ \delta\Omega_y(t_i) = \sum_{j=1}^{M_A} \delta L_j(t_i) C_{yj},\ \delta\Omega_z(t_i) = \sum_{j=1}^{M_A} \delta L_j(t_i) C_{zj}, \tag{5}$$

$\delta L_j(t_i)$ is the length change of the j^{th} bar at time t_i, relative to equilibrium, M_A is the total number of instrumented bars on the alidade, and the coefficients C_{xj}, C_{yj}, C_{zj}, the x, y, z rotational sensitivities of the j^{th} bar in mdeg/meter, are computed from the alidade FEM. The length changes are given by $\delta L_j(t_i) = CL_j\overline{\delta T_j}(t_i)$, where C

is the linear coefficient of expansion for the steel, and $\overline{\delta T_j}(t_i) = \frac{1}{L_j}\int_0^{L_j} \delta T_j(x,t_i)dx$ is the mean temperature change of the j^{th} bar at time t_i, relative to equilibrium.

As of this writing, the 29 most sensitive bars of one of the BWG antennas at the Goldstone tracking station have been instrumented with temperature sensors and insulated, with the joints connecting these to be completed early next year. In order to estimate the temperature profile, $\delta T_j(x,t_i)$, two or three sensors have been mounted on each bar, for a total of 81.

Two different approaches have been used in preliminary tests of the accuracy of the FEM pointing error predictions, one based on tiltmeter readings and the other on direct measurements using the CONSCAN technique. Since the rotations corresponding to a thermally induced XEL pointing error can only be determined by using the alidade FEM itself, only the EL errors can be checked against the tiltmeter readings.

Testing of the partially insulated antenna in the fixed stow position (EL=90 degrees, AZ=180 degrees) over many days has shown reasonably good correlation between the approximately sinusoidal, 4 mdeg diurnal amplitude variations of the FEM predictions and the β_2 readings, but with a significant phase difference between the two. The latter is believed to result from unmodeled temperature variations of the uninsulated joints, and is expected to disappear when the sensitive parts of the structure are fully insulated and instrumented.

The time dependent thermal component of the total EL pointing error has been isolated using CONSCAN measurements on two sources having nearly identical declinations, but right ascensions differing by 1.4 hours. These were tracked over a 7 hour period, spending 10 minutes on each to measure the pointing errors. Shifting the two data records in time by 1.4 hours, subtracting the two, and integrating the result yields the time dependent pointing error, to within an arbitrary constant of integration, and comparison of the EL error obtained this way with the tilt β_2 showed excellent agreement from 4:30 AM to 8:30 AM, but a divergence of the two over the next couple of hours, indicating the onset of another time dependent source of EL pointing error. The source of this divergence, which is approximately equal in magnitude to the alidade errors, is not completely understood at present, but is believed to be due to the onset of heating effects in the upper, tipping part of the antenna structure.

VI. CONCLUSIONS

Several contributions to pointing errors in NASA's 34-m BWG antennas have been identified, and approaches to their reduction explored. Using open-loop CONSCAN to measure pointing errors, accuracies of 0.1 mdeg have been achieved. Comparison of CONSCAN derived errors with those due to the track level irregularities predicted by the TLC system, determined from precision tiltmeter data, show agreement within 0.2 and 0.3 mdeg respectively for the EL and XEL errors at high elevation. Errors induced by thermal distortion of the alidade structure are being reduced by insulating the most sensitive members and actively compensating the residual errors in real time, using temperature measurements of the structure as input to the ATM system, whose output is determined from FEM computations. In addition, hysteresis effects in elevation have been reduced from 4 mdeg to undetectable by improving the elevation encoder coupling design, and azimuth errors due to a segmented encoder ring gear have been reduced from 5.2 to 0.44 mdeg with a new, single piece design. Possible error contributions from the tipping structure are presently being investigated, and the ATM system will be fully tested when the sensor instrumentation and insulation are completed.

VII. ACKNOWLEDGEMENTS

The work described was funded by the TMOD Technology Program and performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.